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Mechanical Properties of Several Magnesium and Aluminum Composites

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13. ABSTRACT *(Maximum 200 words)*

Several composites of magnesium and aluminum alloys were tested in order to assess and evaluate their mechanical properties. The magnesium alloys were AZ91C, ZE41A, and commercially pure magnesium, reinforced with 40% by volume continuous graphite fiber. The tensile properties of these composites were not superior to those of unreinforced magnesium and estimates of their fracture toughness were low. The matrices of the aluminum composites were 2124-T6, 6061-T4, 2124-T4, and 2219-T4. The reinforcements were either particulate or whiskers of silicon carbide or boron carbide and their volume content was 15% to 30%. The aluminum composites which were reinforced with silicon carbide particulate exhibited improved yield and ultimate tensile stresses, as well as tensile elastic modulus over the unreinforced aluminum alloys. The 2124-T4/B_4C/25p composite exhibited the highest ultimate tensile strength which was 511 MPa. The composite which was reinforced with whiskers of silicon carbide exhibited an endurance limit which was 20% higher than that of the matrix alloy. The compressive properties and fracture toughness of some of these aluminum composites were not improved over those of the unreinforced matrix alloy.

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Introduction

Metal matrix composites (MMC) are used to improve the strength-to-weight ratio of structural members. The selection of a MMC for a specific application depends on its mechanical characteristics which, in turn, should fulfill certain design requirements. During the past few years, a number of lightweight MMCs have been tested and characterized for potential U.S. Army applications. These applications include helicopter transmission, landing skid, track pads, and portable bridge elements. This report aims to consolidate the MMC database available at the U.S. Army Materials Technology Laboratory (MTL) for public reference. Some of the data presented in this report such as the magnesium composites have been released previously [1,2]. Two magnesium alloy composites (AZ91C, ZE41A) and a commercially pure magnesium (CP Mg) composite were examined. These matrices were reinforced with 40% by volume continuous graphite fibers. Mechanical property data were also generated for several aluminum composites. The aluminum composites were 2124-T6, 6061-T4, 2124-T4, and 2219-T4 alloys reinforced discontinuously with silicon carbide or boron carbide. The reinforcements were either whiskers or particulate. Tensile, compressive, and fatigue properties, as well as fracture toughness and impact fracture energy, were examined and correlated with the reinforcement volume content and quality of the metal-to-reinforcement bonding.

The system proposed by the Technical Committee on Product Standards of the Aluminum Association was adopted for the designation of the composites discussed herein. The designation consists of the following three parts, each separated from the others by a slash mark: the matrix alloy designation (per American National Standard), the composition of the reinforcement (e.g., SiC), and the volume percent of the reinforcement followed by the type of the reinforcement. The type of the reinforcement is indicated by a lower case letter (f = continuous fiber, p = particulate, w = whisker, and c = cut fibers).

Materials, Specimens, and Test Procedures

The magnesium composites contained 40% by volume continuous P-55 graphite (Gr) fibers. The P-55 Gr fiber was manufactured by AMOCO (Union Carbide). Typical fiber properties (provided by Union Carbide) are shown in Table 1. The average fiber diameter was 10 μm. Prior to consolidation with magnesium, the fibers were immersed in a proprietary organometallic solution and then baked to form a silicon oxide coating. This coating was intended to promote bonding of the fibers with the magnesium matrix. The unidirectionally-reinforced magnesium plates were consolidated by Materials Concept, Inc. using proprietary methods. The chemical composition of the matrix materials is given in Table 2 [1].

Table 1. Properties of Thornel P-55 AMOCO carbon fiber

Tensile strength	=	2,100 MPa
Elastic modulus (E)	=	380 GPa
Density	=	2 (gr/cm^3)
Fiber diameter	=	10 μm

Table 2. Composition of matrix magnesium alloys

Alloy	Al	Mn	Zn	Zr	Ce	Fe	Si	Mg
AZ91C	8.8	0.22	0.48	—	—	0.06	0.50	Bal
ZE41A	—	—	4.20	0.70	1.20	—	—	Bal
CP Mg	—	—	—	—	—	0.60	0.53	Bal

Plates of 2124-T6 aluminum composites were purchased from AVCO (presently TEXTRON). The size of the particulate silicon carbide (SiC) was 8 μm to 36 μm (as estimated metallographically). The silicon carbide whiskers were 12 μm to 36 μm. Plates of 6061-T4, 2124-T4, and 2219-T4 aluminum composites were purchased from DWA. These composites were reinforced with silicon carbide and boron carbie (B_4C) particulates. The respective particle diameters were 8 μm to 24 μm and 16 μm to 88 μm. The volume content of these reinforcements was 15% to 30%.

Tensile tests were conducted with specimens of the types shown in Figures 1 and 2. For the compression tests, cylindrical specimens were used. Fatigue tests were conducted with cylindrical specimens like the one depicted in Figure 2. Charpy bars (see Figure 3) were used for the determination of fracture toughness and impact fracture energy.

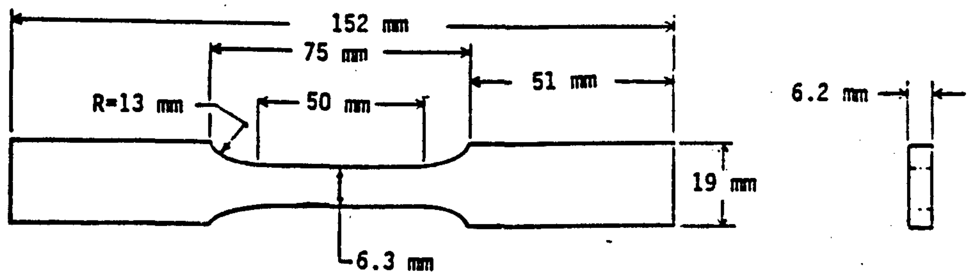

Figure 1. Tension specimen, flat.

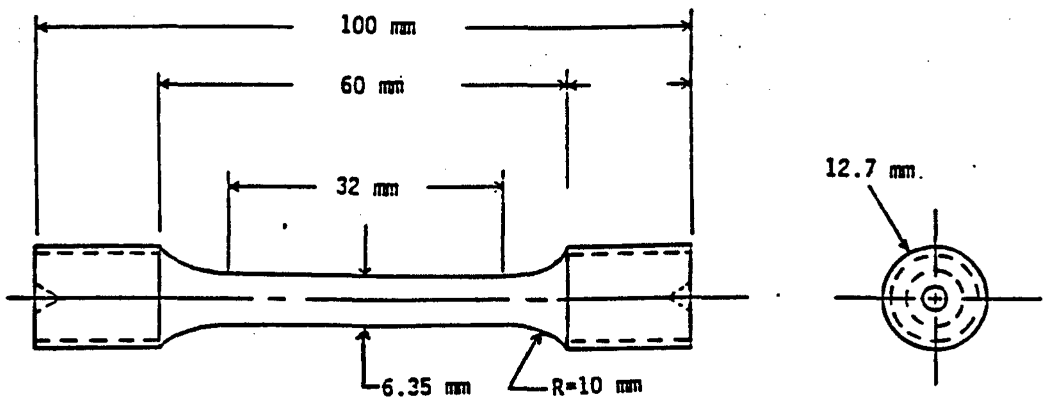

Figure 2. Tension specimen, round, threaded.

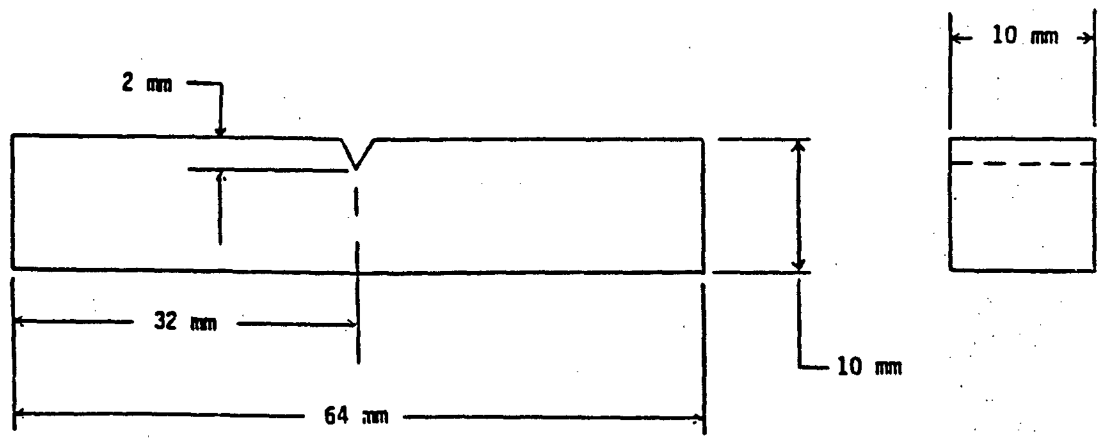

Figure 3. Charpy V-notch specimen.

Test Resul:s and Discussion

Magnesium Composites

Tensile tests for the magnesium composites were conducted on flat specimens as that depicted in Figure 1. The tensile properties of the magnesium composites are listed in Table 3. The Gr/Cp Mg/40f composite exhibited the greatest ultimate tensile strength in the parallel to the fibers direction. The ZE41A matrix composite exhibited the highest elastic modulus E_{11}. The value of the E_{22} modulus, however, indicated some degradation when compared to that of pure magnesium (45 GPa).

Table 3. Tensile properties of Gr/Mg composites [1] (40% by volume graphite fiber, reinforced unidirectionally)

Composite	UTS (MPa) perpendicular to the fibers	UTS (MPa) parallel to the fibers	E_{11} (GPa)	E_{22} (GPa)
Gr/AZ91C	45 ± 10	586 ± 55	184 ± 28	28 ± 2
Gr/ZE41A	19 ± 5	279 ± 41	204 ± 14	25 ± 7
Gr/CP Mg	12 ± 7	658 ± 41	159 ± 21	20 ± 2.7

For the determination of a conditional fracture toughness K_{IQ} of the magnesium composites Charpy bars (bend specimens) were used. These specimens are depicted in Figure 3. The selection of this specimen configuration was based on the findings of a previous study by Tsangarakis, et al [3]. Tsangarakis found that Charpy bars of a continuous fiber-reinforced MMC with a notch as a crack starter gave results comparable to Charpy bars with a saw cut as a crack starter. The former values were 5% to 10% higher than the latter. Fatigue cracking prior to testing for the determination of K_{IQ} was abandoned as it was a cumbersome task under reasonable laboratory conditions. The following crack planes and crack growth direction combinations were examined: LT, LS, TL, and TS (for the details of these designations see ASTM E-399 standard).

At least six Charpy bars were tested per composite, crack plane, and crack growth direction. For a description of the respective test procedure, the reader is referred to the ASTM standard procedures E-399. Fracture toughness values of the magnesium composites obtained from Charpy bars are shown in Table 4. For the LT and LS crack plane orientations the composite AZ91C/Gr/40f produced the highest K_{IQ} values, 2.50 and 1.60 MPa$\sqrt{m}$, respectively. These values, however, are extremely small. Two specimens of this composite of the LT crack plane orientation produced even smaller values of K_{IQ}. The fracture toughness value for both specimens was 0.33 MPa$\sqrt{m}$. Because both specimens exhibited numerous fiber pullouts on their fracture surfaces, it will be inferred that the low K_{IQ} values were the result of an inadequate bonding between matrix and fibers. The inadequate bonding between matrix and fibers produced an easy path for the growing cracks to follow (this easy path being the matrix/fiber interface) thus leading to low fracture toughness values. The same composite also produced low K_{IQ} values for crack plane orientations which were parallel to the graphite fibers. These values were 0.09 MPa$\sqrt{m}$ and 0.15 MPa$\sqrt{m}$ for the TL and TS crack plane orientations, respectively. The fracture toughness on planes parallel to the fibers was at least four times less than on planes perpendicular to the fibers. Although the methods used to produce these conditional fracture toughness values have not been approved by any organization; e.g., ASTM, their magnitudes are extremely small indicating property degradation and not improvement.

Table 4. Charpy fracture toughness K_{IQ} (MPa$\sqrt{m}$)^2 magnesium composites

Crack plane orientation	Gr/AZ91C	Gr/ZE41A	Gr/CP Mg
LT	2.50 ± 0.15	1.32 ± 0.13	1.54 ± 0.18
LS	1.60 ± 0.69	1.21 ± 0.08	1.40 ± 0.19
TL	0.09 ± 0.08	0.24 ± 0.05	0.20 ± 0.08
TS	0.15 ± 0.09	0.31 ± 0.09	0.20 ± 0.04

Standard size Charpy V-notch bars of magnesium composites were tested in impact (ASTM E 23-86 test procedure) to assess their impact fracture energy, which is a measure of their toughness. The Charpy impact fracture energies are listed in Table 5. From these energy values it may be inferred that the CP Mg/Gr/40f is the superior composite. It should be noted that in all the magnesium composites the fracture energy along planes parallel to the fibers were at least one order of magnitude less than the fracture energy on planes perpendicular to the fibers.

Table 5. Charpy fracture energy (Joules) magnesium composites

Orientation	Gr/AZ91C	Gr/ZE41A	Gr/CP Mg
LT	1.65 ± 0.42	0.96 ± 0.25	3.86 ± 0.82
LS	2.60 ± 0.86	1.39 ± 0.28	3.24 ± 0.36
TL	0.008 ± 0.013	0.030 ± 0.013	0.194 ± 0.147
TS	0.026 ± 0.019	0.031 ± 0.009	0.116 ± 0.022

Aluminum Composites

All the tensile tests on the aluminum composites and matrices were conducted with cylindrical specimens with threaded ends. These tensile specimens are depicted in Figure 2. Results of the tensile tests on the aluminum matrix and its composites are given in Table 6. The addition of 30 v/o SiC whiskers and 15 v/o SiC particulate to the 2124-T6 aluminum caused little or no improvement of the 0.2% yield stress and ultimate tensile stress (UTS). However, the addition of 30 v/o SiC particulate caused a 22% improvement of the matrix yield and ultimate tensile stresses. All reinforcements caused noticeable improvement of the matrix elastic modulus. The 30 v/o SiC particulate addition produced a 71% increase of the modulus value. One should notice, however, the drop in the value of the strain to failure. The latter is a measure of the composite's machinability and formability. The 2124-T4/B_4C/25p composite exhibited an excellent strength improvement over the 2124-T6/SiC/30p. Because the UTS improvement in 2124-T4/B_4C/25p was 39%, it is recommended that this composite should be examined more closely.

Table 6. Tensile properties (aluminum and composites)

Material	0.2% YS (MPa)	UTS (MPa)	E (GPa)	Strain
2124-T6/SiC/15p	199 ± 2.0	259 ± 2.4	84 ± 6.2	0.053
2124-T6/SiC/30p	254 ± 5.0	367 ± 3.6	120 ± 9.0	0.040
2124-T6/SiC/30w	212 ± 3.3	323 ± 4.6	81 ± 6.6	0.095
2124-T6/SiC/30w	179 ± 1.6	283 ± 1.7	91 ± 9.0	0.098
2124-T6 aluminum	208 ± 3.0	305 ± 4.5	70 ± 4.1	0.145
6061-T4/SiC/15p	341 ± 8.0	434 ± 10	94 ± 1.0	0.050
6061-T4/B_4C/20p	369 ± 2.0	416 ± 2.0	104 ± 4.0	0.034
2124-T4/B_4C/25p	381 ± 5.0	511 ± 13	119 ± 3.0	0.022
2219-T4/B_4C/15p	315 ± 25	421 ± 27	98 ± 3.0	0.021

NOTE: 0.2% YS = Yield stress
UTS = Ultimate tensile stress
E = Young's modulus
Strain = Strain to failure

The compressive properties of several discontinuously reinforced aluminum composites and the aluminum matrix are listed in Table 7. Compression tests were conducted with solid cylinders 30 mm high and 20 mm in diameter. The ASTM E-9 test procedure was followed and TEFLON™ sheets were used between the specimens and the tungsten carbide loading plates to minimize friction. The crosshead displacement was monitored with a linear variable differential transducer (LVDT) and a longitudinally oriented strain gage (positioned in the middle of the height of the specimen) was used to monitor the strain. The specimens of each material were separated arbitrarily into two groups, each group containing at least three specimens. Calculation of the elastic modulus using the strain gages' output produced better values compared to LVDT. The maximum compressive stress (MCS) corresponds to the "reduction of height" presented in the last column of the table. This stress was calculated with the prior to testing cross-sectional area. The "reduction of height" listed in the last

column was estimated with a LVDT. No significant improvement of the MCS over that of the pure matrix was achieved by the reinforcements; on the contrary, the "reduction of height" to failure was significantly reduced. Failure of the cylinders was coincident with the drop in the load and the generation of lateral cracks in the specimens (see Figures 4 and 5). The modulus of elasticity was also reduced in the reinforced material by 9% to 41%. The degradation of the mechanical property values could be due to inadequate bonding of the reinforcements with the matrix. In this case, the presumably reinforced matrix areas acted like cavities which were deformed by, but did not contribute the appropriate resistance to the applied load.

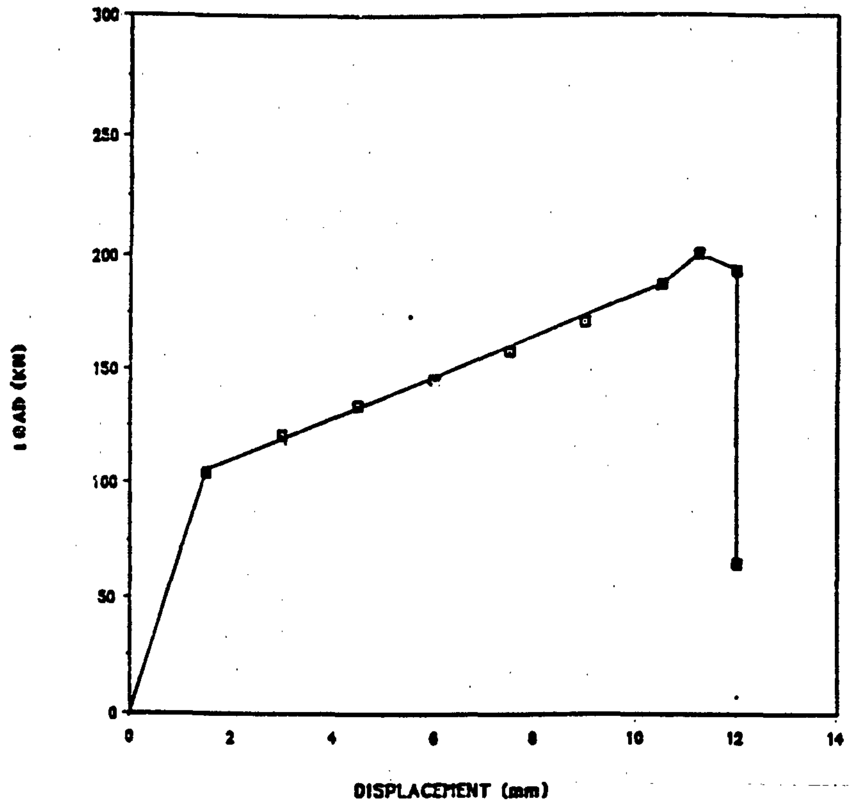

Figure 4. Load versus displacement curve for the 2124-T6/SiC-15w.

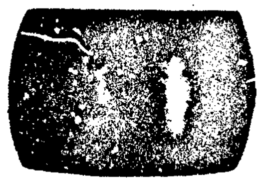

Figure 5. Compression cracks.

Table 7. Compressive properties of 2124-T6 reinforced aluminum

Material	0.2% Yield stress (MPa)	Maximum stress (MPa)	Modulus E (GPa)	Reduction of height (mm)
2124-T6/SiC/15p	205 ± 17	564 ± 24	56 ± 5.5	-9.09
	203 ± 21	565 ± 21	56 ± 2.8	-9.09
2124-T6/SiC/15w	203 ± 3	615 ± 10	43 ± 14	-11.15
	203 ± 1	616 ± 11	44 ± 8	-10.29
2124-T6/SiC/30w	265 ± 6	655 ± 8	63 ± 13	-8.13
	265 ± 0	649 ± 2	59 ± 8	-7.92
2124-T6	214 ± 3	662 ± 1	75 ± 0	-16.94
2124-T6	216 ± 3	660 ± 1	66 ± 3	-16.51

NOTE: The reduction of height listed in the last column corresponds to the onset of a visible specimen crack and a drop of the applied load.

All stresses were calculated with prior testing cross-sectional areas.

Fatigue test results for the aluminum 2124-T6 matrix and its composites are listed in Table 8. The fatigue test specimens were cylindrical with threaded ends, similar to those used for the tensile tests (see Figure 2). Fatigue tests were conducted with a frequency of 40 Hz and a stress ratio R = 0.1 in a 45 KN Instron servohydraulic test machine. The matrix endurance limit for 10^7 cycles was 179 MPa. With 15% SiC_w reinforcement the endurance limit was upgraded to just below 214 MPa. With 30% SiC_w reinforcement the endurance limit remained at 214 MPa. Thus, a 15% reinforcement achieved full strengthening of the composite. The improvement was nearly 20% of the matrix endurance limit.

Table 8. F[illegible] properties of aluminum and composites

Material	Maximum stress (MPa)	Cycles to failure
2124-T6/SiC/15p	186	11,450
	214	10,170
	234	3,000
2124-T6/SiC/15w	214	10,000,000
	214	5,716,000
	234	210,000
	255	81,000
	269	92,000
2124-T6/SiC/30w	214	10,000,000
	255	272,000
	255	6,214,000
	262	86,679
	262	206,000
	276	1[illegible]3,310
	276	262,000
	290	83,300
	303	28,000
2124-T6	179	10,000,000
	200	496,000
	207	877,100
	221	125,573
	227	85,570

NOTE:
Specimen diameter: 5.00 mm
Specimen gage length: 25.00 mm
Fatigue frequency: 40 Hz
Stress ratio (min/max) = R: 0.1

For the determination of a conditional fracture toughness of aluminum composites reinforced discontinuously with SiC whiskers or particulates, the bend specimen was used. The length, width, thickness, and notch depth of these specimens were 86 mm, 19 mm, 9.6 mm, and 8 mm, respectively. These specimens were fatigue-cracked and tested per ASTM E-399 standard test procedure. Fracture toughness values for the discontinuously reinforced aluminum composites are given in Table 9. The majority of these test results did not satisfy the ASTM E-399 test criteria to produce K_{IQ} values qualifying for K_{IC}. Instead, the fracture toughness values shown represent conditional values only. As it can be inferred from the data in Table 8, the reinforcements did not improve the fracture toughness of the matrix alloy. The conditional fracture toughness values shown in the table are in agreement with those found by K. Salama, et al [4].

Table 9. Fracture toughness of aluminum composites

Composite	K_{IQ} (MPa$\sqrt{m}$)	Number of specimens
2124-T6/SiC/30w	16.65 ± 1.4	12
2124-T6/SiC/15w	16.30 ± 0.5	5
2124-T6/SiC/15p	16.72 ± 1.4	5
2124-T6 aluminum	16.42 ± 1.2	3

Summary

The Gr/CP Mg/40f composite exhibited the greatest ultimate tensile strength in the parallel to the fibers direction. In the discontinuously reinforced composites of aluminum, significant improvements were noted in the yield and ultimate tensile strengths and the tensile modulus by the 30 v/o SiC particulate. The 2124-T4/B_4C/25p composite exhibited the highest ultimate tensile strength which was 511 MPa. Some improvement (20%) of the endurance limit was caused by the addition of 15% SiC whiskers.

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